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Future prospects for inference on solar-type stars

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Abstract.

We discuss prospects for asteroseismic inference on solar-type stars, in particular opportunities that are being made possible by the large ensemble of exquisite-quality *Kepler* data.

1. Introduction

The observational basis for stellar physics is being enhanced significantly by a new era of satellite and ground-based telescope observations of unprecedented quality and scope. The recent launch of the NASA *Kepler Mission* has meant a huge breakthrough in amount and quality of data for the study of solar-type stars using the techniques of asteroseismology (Gilliland et al. 2010, Chaplin et al. 2010).

Thanks to *Kepler* the number of solar-type stars with good seismic observations has increased from about 20 to several-hundred (Chaplin et al. 2011a; see Fig. 1). The French-led CoRoT satellite (Michel et al. 2008, Appourchaux et al. 2008) also continues to provide high-quality asteroseismic data on a smaller number of solar-type stars. It is based on these dramatic improvements in data quality and quantity that exciting new results from asteroseismology are feeding into studies in stellar physics, exoplanets, galactic and extra-galactic physics and cosmology.

2. Overview: opportunities for seismic analysis of solar-type stars

Solar-type stars have sub-surface convection zones and, like the Sun, display solar-like oscillations. The rich information content of these seismic signatures means that the fundamental stellar properties (e.g., mass, radius, and age) may be measured and the internal structures constrained to levels that would not otherwise be possible (e.g., see Gough 1987; Cunha et al. 2007; Aerts et al. 2010). While helioseismology has shown that we can model $\sim 1 M_{\odot}$ stars quite well, we do not yet now if we can model more massive stars with convective cores properly (the sizes of the convective cores, and the amount of core overshoot, affect the main-sequence lifetimes of the stars; e.g., see Cunha & Metcalfe 2007). Multi-month observations of solar-type targets with *Kepler* will allow us to obtain accurate and precise estimates of the basic parameters of *individual modes*, such as frequencies, frequency splittings, amplitudes, damping rates, and asymmetries of the resonant peaks, covering many radial orders.

Multi-month and multi-year data on a sizable ensemble of solar-like oscillators opens the possibility to:

- study the internal rotation rates of solar-type stars, compare internal and surface rates of rotation, test theories of angular momentum evolution, and test and calibrate gyrochronology;
- measure the helium abundances, and signatures of convective cores, to test theories of stellar evolution;
- measure the depths of the sub-surface convective envelopes, signatures of stellar cycles and the acoustic asphericities, to test dynamo theories; and
- study the interaction of convection with the solar-like oscillations, using information from the frequency dependence of mode amplitudes, mode damping rates and mode peak asymmetries;

Use of individual frequencies increases the information content provided by the seismic data (e.g., see Monteiro et al. 2000). The frequencies offer the potential for inferring the radial structure inside stars (e.g., Basu et al. 2001; Roxburgh & Vorontsov 2003); they also allow detection of signatures of regions of abrupt structural change in the stellar interiors, e.g., the near-surface ionization zones and the bases of the convective envelopes (see Houdek & Gough 2007, and references therein). Inference on the ionization zone signatures in principle allows constraints to be placed on the envelope He abundances (e.g., Mazumdar et al. 2006); while estimation of the depths of the convective envelopes will provide key information for the dynamo modellers.

Asteroseismology can provide precise estimates of ages of solar-type stars. Inference on ages of course relies on stellar evolutionary theory. The stellar models must include all of the requisite physics that we consider to be significant in determining the evolutionary status of the star, and as a result its observable properties. Inaccuracies in the descriptions of these quantities may of course lead to systematic errors in estimates of the fundamental stellar properties. There are uncertainties related to modelling of, for example, convective motions and convective overshooting at the convective boundaries, microscopic diffusion, and the impact of dynamical processes such as instabilities and flows associated with internal rotation. It will be possible to use precise data on the oscillation frequencies to constrain the input physics to the stellar evolutionary models.

With asteroseismic ages in hand it will, for example, be possible to validate methods of ageing stars based on the observed surface rates of rotation (gyrochronology; see Barnes 2003). These surface signatures may be detected, and then quantified, in the *Kepler* and CoRoT lightcurves. From the long datasets it is possible to extract estimates of frequency splittings of non-radial modes, which have contributions from internal rotation and magnetic fields. This opens the possibility to study the relationship between the mean internal rotation and the surface rates of rotation in the solar-type ensemble. Measurement of asymmetries of the frequency splittings also allows constraints to be placed on the surface distributions of active regions (e.g., see Chaplin et al. 2007; Chaplin 2011), results that may be compared with inferences drawn from modelling of the surface signatures of rotation. And it is also possible to estimate stellar angles of inclination from measurement of the amplitude ratios of components of non-radial modes (e.g., see Gizon & Solanki 2003; Ballot et al. 2006).

The observed oscillation modes in these solar-type stars are intrinsically stable (e.g. Balmforth 1992a; Houdek et al. 1999) but driven stochastically by the vigorous

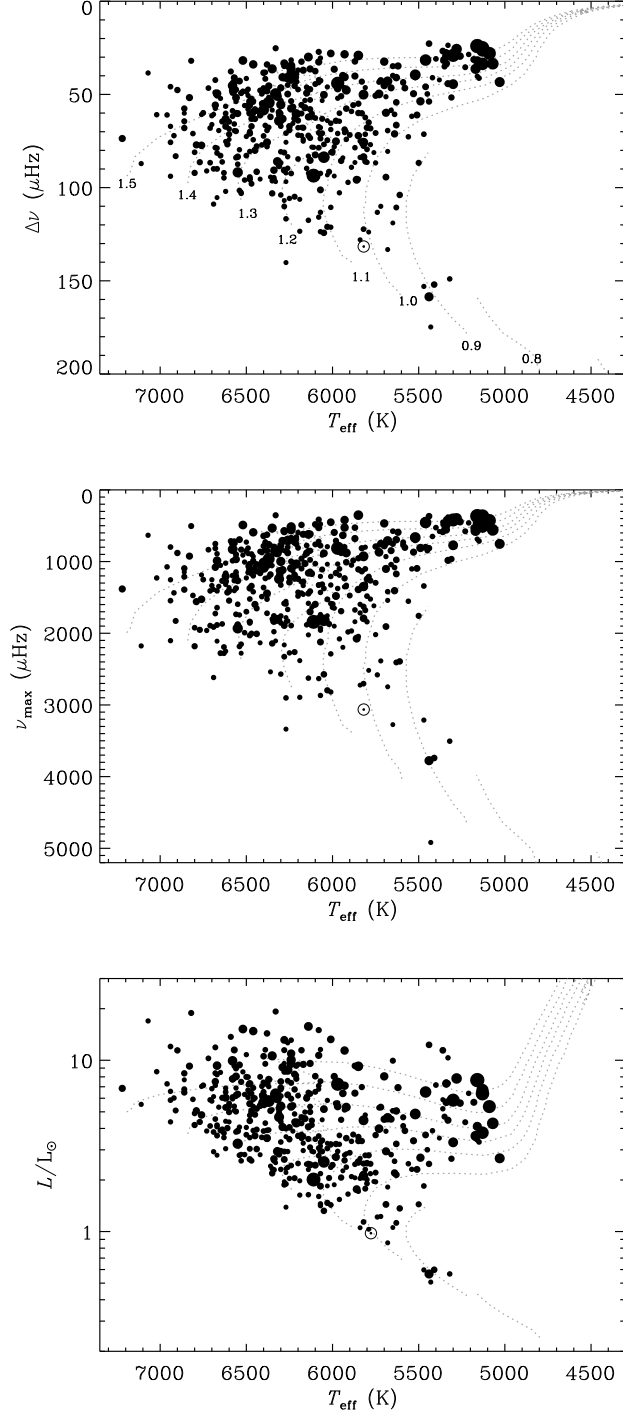


Figure 1. Results from *Kepler* on solar-type stars with detectable oscillations. Plotted, versus effective temperature T_{eff} , are: Observed average large frequency separations, $\Delta\nu$ (top panel); observed frequencies of maximum oscillations power, ν_{max} (middle panel); observed luminosities $L \propto R^2 T_{\text{eff}}^4$, computed from the seismically determined radii, R (bottom panel). Symbol sizes are proportional to observed SNR_{tot} . The location of the Sun is marked with the usual solar symbol. The dotted lines are evolutionary tracks (Padova models) for solar composition, computed for masses ranging from 0.7 to 1.5 M_{\odot} (Girardi et al. 2002, 2004; Marigo et al. 2008).

turbulence in the superficial stellar layers (e.g. Goldreich & Keeley 1977; Balmforth 1992b; Samadi & Goupil 2001). Solar-like mode peaks have an underlying form that follows, to a reasonable approximation, a Lorentzian. The widths of the Lorentzians provide a measure of the linear damping rates, while the amplitudes are determined by the delicate balance between the excitation and damping. Small departures from the Lorentzian form – which makes the peaks asymmetric – provide information on the location and properties of the acoustic sources, and correlation of the oscillations with the stellar granulation. Accurate and precise measurement of these various parameters, and their variation in frequency, provides the means to infer various important properties of the still poorly understood near-surface convection.

Further inferences on near-surface physics may potentially be acquired by differential seismic analyses of simultaneous observations of the same star made in photometry and Doppler velocity. For example, there is the exciting prospect of our having simultaneous data on the solar-type binary 16 Cyg from observations made in photometry by *Kepler* and in Doppler velocity by the Stellar Observations Network Group (SONG) (Grundahl et al. 2009). The opportunities for collecting simultaneous data in photometry and Doppler velocity may be limited in the near future to only a small number of stars, and as such it also behoves us to look for twins of *Kepler* and CoRoT stars in data already collected by ground-based telescopes.

Finally, extended observations of solar-type targets spanning several years will allow us to “sound” stellar activity cycles, by detecting systematic changes in mode parameters such as frequencies, amplitudes and damping rates (e.g., see Chaplin et al. 2007; Metcalfe et al. 2007; Karoff et al. 2009).

3. Ensemble studies

Kepler is opening exciting new opportunities to conduct *ensemble seismology* thanks to the large number of stars being observed. The large, homogeneous *Kepler* ensemble will for the first time allow a seismic survey of a population of solar-type field stars to be made. A statistical survey of trends in important seismic parameters will allow tests of basic scaling relations, comparisons with trends predicted from modelling, and lead to important insights on the detailed modelling of stars. This work is now in progress (e.g., see Chaplin et al. 2011b, Huber et al. 2011, Verner et al. 2011, White et al. 2011a)

One may also pick from a large ensemble pairs, small groups or sequences of stars that share common stellar properties, e.g., mass, composition, or surface gravity, e.g., Silva-Aguirre et al. (2011a) demonstrate selection of a $1 M_{\odot}$ sequence of *Kepler* stars. With selected data of this type we can perform what one might term *differential* (or *comparative*) seismology of stars, e.g., in analysing the selected stars one may eliminate or suppress any dependence of the modelling or results on the common property, or properties. By selecting, for example, a sequence of stars of very similar mass and composition it is possible to produce an exceedingly accurate and robust relative age calibration, and give the potential to map evolutionary sequences of internal properties and structures, allowing exquisite tests of stellar evolutionary models. By selecting stars with very similar surface gravities, one may potentially probe differences in near-surface physics and convection.

4. Inference on regions of abrupt structural change in stellar interiors

Regions of stellar interiors where the structure changes abruptly, such as the boundaries of convective regions, give rise to departures from the regular frequency separations implied by an asymptotic description. Allowance must be made for the signatures of these changes to in principle avoid biases in the inferred fundamental properties. This might seem like an unwanted complication. However, careful measurement of these signatures not only brings cleaner inference on the properties – i.e., the signatures can first be removed from the mode frequencies before the direct fitting is performed – but it also elucidates other important parameters and physical properties of the stars. There are signatures left by the ionization of helium in the near-surface layers of the stars. Measurements of these signatures allow tight constraints to be placed on the helium abundance, something that would not otherwise be possible in such cool stars (because the ionization temperatures are too high to yield usable photospheric lines for spectroscopy). And as noted above, there are also signatures left by the locations of convective boundaries. It is therefore possible to pinpoint the lower boundaries of convective envelopes. These regions are believed to play a key rôle in stellar dynamos. Furthermore, it is also possible to estimate the sizes of convective cores. Measurement of the sizes of these cores, and the overshoot of the convective motions into the layers above, is important because it can provide an even more accurate calibration of the ages of the affected stars. The mixing implied by the convective cores, and the possibility of mixing of fresh hydrogen fuel into the nuclear burning cores – courtesy of the regions of overshoot – affects the main-sequence lifetimes (e.g., see Mazumdar et al. 2006).

The characteristics of the signatures imposed on the mode frequencies depend on the properties and locations of the regions of abrupt structural change. When the regions lie well within the acoustic cavities, a periodic component is manifest in the frequencies. The period of the signature relates to the acoustic radius of the region, while the amplitude of the signature provides a measure of the size of the effect. Two signatures of this type have already been well studied in the solar case: one due to the discontinuity in the gradient of the sound speed at the base of the convective envelope; and another due to changes in the adiabatic exponent in the near-surface helium ionization zones.

While the periodic signatures from the helium ionization zones may already be readily apparent in the large frequency separations, their signals may be better isolated by, for example, taking second differences of frequencies of modes having the same angular degree l (e.g., Basu et al. 2004), or by subtracting the frequencies from a smoothly varying function in the overtone number, n (Verner, Chaplin & Elsworth 2006). The signature from the base of the convective envelope is also apparent in the second differences, although at a reduced amplitude compared to the helium signature. Better diagnostics from which to extract the convective-envelope signature are instead frequency differences that make use of the $l = 0$ and $l = 1$ modes (Roxburgh 2009). In the p-mode frequency spectrum, modes of odd angular degree lie about halfway between modes of even angular degree. The diagnostics are provided by the deviations of the $l = 0$ and $l = 1$ mode frequencies from the exact halfway frequencies.

The key to extracting these signatures in other solar-type stars is to have sufficient precision in estimates of the frequencies. Basu et al. (2004) have shown that it should be possible to extract the helium signatures from solar-type main-sequence stars provided the frequencies are estimated to a precision of at least ≈ 1 part in 10,000. Similar constraints are imposed in respect of the measurement of the signatures of the bases of the

convective envelopes (e.g., see the tests undertaken by Ballot, Turck-Chi  ze & Garc  a 2004, and Verner, Elsworth & Chaplin 2006). Extraction of the helium signatures allows an estimate to be made of the helium abundance in the stellar envelopes. This should be possible to a precision of 1 to 2 per cent. While extraction of the convective-envelope signature provides a well-constrained estimate of the acoustic radius of the envelope, and also allows constraints to be placed on the overshoot into the radiatively stratified layer below (e.g., see Monteiro, Christensen-Dalsgaard & Thompson 2000).

When regions of abrupt structural change do not lie well within the mode cavities, the signatures they leave are more subtle. This is the case for the signatures left by small convective cores found in solar-type stars that are slightly more massive than the Sun (Cunha & Metcalfe 2007). Suitable combinations of the mode frequencies can provide sensitive diagnostics not only of the presence of convective cores, but also of their size (Cunha & Brand  o 2011; Silva-Aguirre et al. 2011b). Soriano & Vauclair (2008) have also shown how the abrupt gradients at the edges of the convective cores can cause the small frequency separations to reverse their sign. Measurement of the separations can therefore also serve to elucidate the presence, and then constrain the properties of, the cores.

5. Diagnostic potential of modes of mixed character

Next, we touch on the diagnostic potential of avoided crossings (Osaki 1975; Aizenman et al. 1977) in solar-type stars. These avoided crossings are a tell-tale indicator that the stars have evolved significantly. In young solar-type stars there is a clear distinction between the frequency ranges that will support acoustic (pressure, or p) modes and buoyancy (gravity, or g) modes. As stars evolve, the maximum buoyancy (Brunt-V  is  l  ) frequency increases. After exhaustion of the central hydrogen, the buoyancy frequency in the deep stellar interior may increase to such an extent that it extends into the frequency range of the high-order acoustic modes. Interactions between acoustic modes and buoyancy modes may then lead to a series of avoided crossings, which result from the frequencies being “bumped”, with the affected modes taking on mixed p and g characteristics. Measurement of the frequency signatures of these avoided crossings has the potential to provide exquisite constraints on the fundamental stellar properties (Bedding 2011). Very little data had been available historically. Observational evidence for avoided crossings had been uncovered in ground-based asteroseismic data on two bright stars, η Boo and β Hyi (Christensen-Dalsgaard et al. 1995; Kjeldsen et al. 1995; Bedding et al. 2007; Do  an et al. 2010). Deheuvels et al. (2010) also recently reported evidence for avoided crossings in CoRoT observations of the G-type star HD49385, with Deheuvels & Michel (2010) using an elegant analysis based on coupled oscillators to discuss the results. *Kepler* now promises dramatic changes in this area, because within the large *Kepler* ensemble of solar-like oscillators there is a clear selection of stars showing avoided crossings. One of the three solar-like stars selected for the first *Kepler* paper on solar-like oscillators – KIC 11026764 – is a beautiful case in point, and has been the subject of further in-depth study (Metcalf et al. 2010a). The data provided by *Kepler* will by necessity drive developments in analysis to allow the diagnostic potential of avoided crossings to be fully exploited, work that is already in progress (e.g., see discussion of the new so-called p-g diagram in Bedding 2011, and White et al. 2011b).

6. Seismic diagnostics of stellar cycles

The availability of long timeseries data on solar-type stars, courtesy of the *Kepler* and CoRoT is now making it possible to “sound” stellar cycles with asteroseismology. The prospects for such studies have been considered in some depth (e.g., Chaplin et al. 2007, 2008; Metcalfe et al. 2008; Karoff et al. 2009), and in the last year the first convincing results on stellar-cycle variations of the p-mode frequencies of a solar-type star (the *F*-type star HD49933) were reported by García et al. (2010). This result is important for two reasons: first, the obvious one of being the first such result, thereby demonstrating the feasibility of such studies; and second, the period of the stellar cycle was evidently significantly shorter than the 11-yr period of the Sun (probably between 1 and 2 yr). If other similar stars show similar short-length cycles, there is the prospect of being able to “sound” perhaps two or more complete cycles of such stars with *Kepler* (assuming the mission is extended, as expected, to 6.5 yr or more). The results on HD49933 may be consistent with the paradigm that stars divide into two groups, activity-wise, with stars in each group displaying a similar number of rotation periods per cycle period (e.g., see Böhm-Vitense 2007), meaning solar-type stars with short rotation periods – HD49933 has a surface rotation period of about 3 days – tend to have short cycle periods. We note that Metcalfe et al. (2010b) recently found another *F*-type star with a short (1.6 yr) cycle period (using chromospheric H & K data). Extension of the *Kepler* Mission will of course also open the possibility of detecting full swings in activity in stars with cycles having periods up to approximately the length of the solar cycle.

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